Bond Graph Modeling of a Robot Manipulator

F.Z.BAGHLI, L. EL BAKKALI

Modeling and Simulation of Mechanical Systems Laboratory, Abdelmalek Essaadi University, Faculty of Sciences, BP.2121, M'hannech, 93002, Tetuan, Morocco

baghli.fatimazahra@gmail.com

Abstract:

In this paper we propose a new approach for modelling a robot arm based on Bond Graph methodology. The proposed method based on the transfer of energy between system components and on the description of the vector velocity relation of a moving point in a rotating system.
Our system is a double freedom robot manipulator driving by an electric actuator, can be efficiently modelled and solved by this multidisciplinary approach.

Résumé:

Dans ce travail, nous proposons une nouvelle approche de modélisation d'un robot manipulateur basé sur la méthodologie Bond Graph. Cette méthode est basée sur le transfert d'énergie entre les composants du système en utilisant des liens de puissance.

Keywords: Bond Graph, Robot manipulator, Modelling.

1 Introduction

A good modelling of the specific manipulator needs an efficient method to describe all behaviors of system.
The Newton-Euler technique and Lagrange's technique are the most methods used for dynamic modelling; these techniques calculate a vector containing the force or torque required at each joint to attain a specified trajectory of joint positions, velocities and accelerations. The main disadvantages of the above modelling techniques are their complexity and lack of versatility [1].
The Bond Graph technique developed since the 1960's represent a powerful approach to modelling robotic manipulators and mechanisms [1][2].It is a graphical representation that depicts the interaction between elements of the system along with their cause and effect relationships. The use of Bond Graph to describe all behaviors of robotic manipulators can he developed based on kinematic relationships between the time rates of joint variables and the generalized Cartesian velocities (translational and angular velocities) [2].This efficient method can be used to obtain more information such as the power required to drive each joint actuator, or the power interaction at the interface with the environment, Such information can also be used to study the performances like stability, precision of the manipulator system.

In this work the study is extended to a highly non linear, multiple inputs multiple outputs (MIMO) system, this study is illustrated by the two arms manipulator. The aim of this work is to describe all behaviors of our system by using bond Graphs.

2. The Bond Graph

2.1 Bonds

The basic element of bond graphs is the energy bond (Figure 1) , in this method, power consists of two variables which are known as generalized effort generalized flow denoted by e and f respectively; these two variables are necessary and sufficient to describe the energetic transfers inside the system. The physical meaning of the effort and flow variables depends upon the physical domain the bond represents. A unidirectional semi headed arrow shows this energy interchange (the arrow on the bond denotes the direction of positive energy flow). Table 1 gives examples of the effort and flow variables for mechanical and electrical domains.

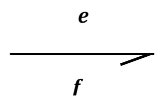


Figure 1: Energy bond

Domain	Effort (e)	Flow (f)
Translation Mechanics	Force	Velocity
Rotational Mechanics	Torque	Angular velocity
Electricity	Voltage	Current

Table 1: Effort and Flow variables in some physical domains

2.2. Components

There are four types of components labeled S, C, I, R, this elementary components are classified by their energetic behavior (energy dissipation, energy storage, etc.) and define how the effort and flow variables on the bond relate to each other. The table 2 show the elementary component of bond graph.

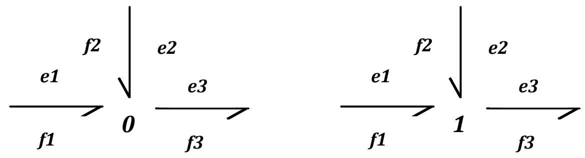
Component	Symbol	Type of element	Example in translation mechanic domain	Example in rotational mechanic domain	Example in electric domain
Active elements	Se	Effort source	Force source	Torque source	Voltage source
	Sf	Flow source	Velocity source	Angular velocity source	Current source
Passive elements	R	Dissipation	Damper	Rot. Damper	Resistor
	I	Storage	Inertia	Rot. Inertia	Inductor
	C		Compliance	Rot. Compliance	Capacitor

Table 2: Basic Bond Graph elements

2.3. Junctions

Components are connected together using two types of junctions: a 0 or common effort junction and a 1 or common flow junction.

The 0 junction has the following properties: all bonds impinging upon it have the same effort variable and all flows on attached bonds sum to zero. Similarly the 1 junction has the properties: all bonds impinging upon it have the same flow variable and all effort on attached bonds sum to zero.



e1=e2=e3 ; f1+f2-f3=0 ***f1=f2=f3 ; e1+e2-e3=0***

a) 0-Junction b) 1-Junction

Figure 2: Illustration of junction

2.4 Connecting mechanical and electrical domains

To transfer between physical domains the ability to multiply must be included and bond graphs provide two means of accomplishing this: the Transformer TF and the Gyrator Gy (TF or Gy are energy conserving).

3. Description of the robot manipulator

In this section, geometric and kinematic models are used for modeling the behavior of a robot manipulator with 2DOF.

The parameters of the system are joint and operational positions, the first allows modifying its geometry and the second determines the position and the orientation of the end effector M. In Figure 3 a schema is given of 2-link rigid arm in which each articulation is driven individually by an electric actuator:

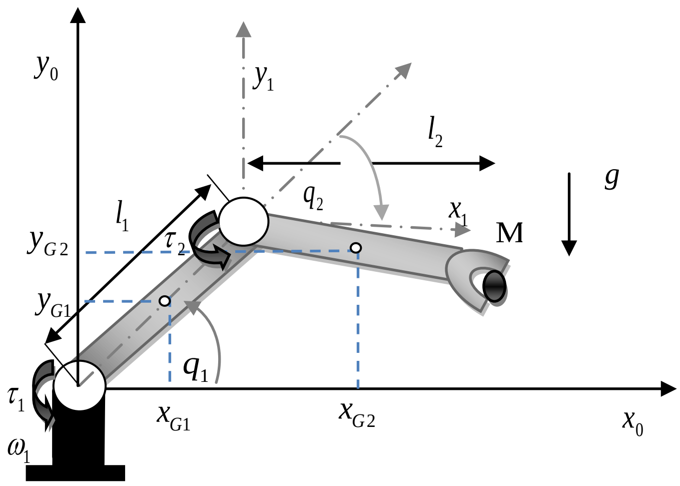


Figure 3: Structure of manipulator robot of two degree of freedom

The positions and the velocities of the centers of mass of the two links are described by following equations as shown in figure

$$x_{G1} = \frac{l_1}{2}\cos(q_1) \qquad 1)$$

$$y_{G1} = \frac{l_1}{2}\sin(q_1) \qquad 2)$$

$$x_{G2} = l_1\cos(q_1) + \frac{l_2}{2}\cos(q_1+q_2) \qquad 3)$$

$$y_{G2} = l_1\sin(q_1) - \frac{l_2}{2}\sin(q_1+q_2) \qquad 4)$$

$$vx_{G1} = -\omega_1\frac{l_1}{2}\sin(q_1) \qquad 5)$$

$$vy_{G1} = \omega_1\frac{l_1}{2}\cos(q_1) \qquad 6)$$

$$vx_{G2} = -\omega_1 l_1\sin(q_1) - \frac{l_2}{2}(\omega_1+\omega_2)\sin(q_1+q_2) \qquad 7)$$

$$vy_{G2} = \omega_1 l_1\cos(q_1) + \frac{l_2}{2}(\omega_1+\omega_2)\cos(q_1+q_2) \qquad 8)$$

4. Bond graph for a rotating arm

The bond graph for the first arm is derived from expressions of the velocities of the center of mass 5 and 6

The transformers are used to convert the angular velocity to a linear velocity and the dynamics can be introduced by adding I element to the arm as shown in figure 4.

The base of the second arm is not fixed in space but depends on the velocity of its attachment point to the first arm, therefore, the development of the first and the second arm based on the expressions of the velocities of center mass of the second link.

The complete bond graph of our system is shown in figure 5:

Where:

$$r_1 = -l_1\sin(q_1) \qquad (9)$$

$$r_2 = l_1\cos(q_1) \qquad (10)$$

$$r_3 = -l_2\sin(q_2) \qquad (11)$$

$$r_4 = -l_2\cos(q_2) \qquad (12)$$

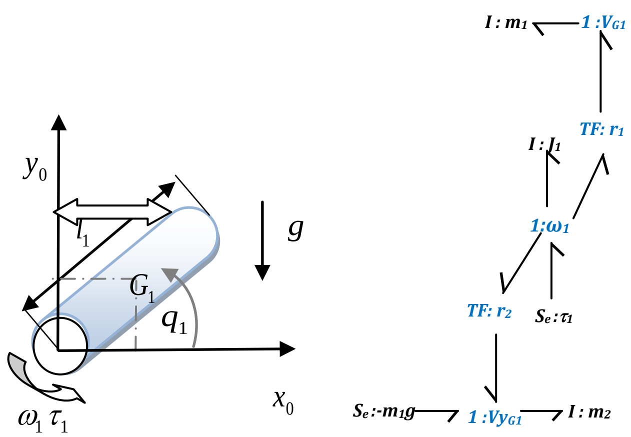


Figure 4: Bond graph of the first link

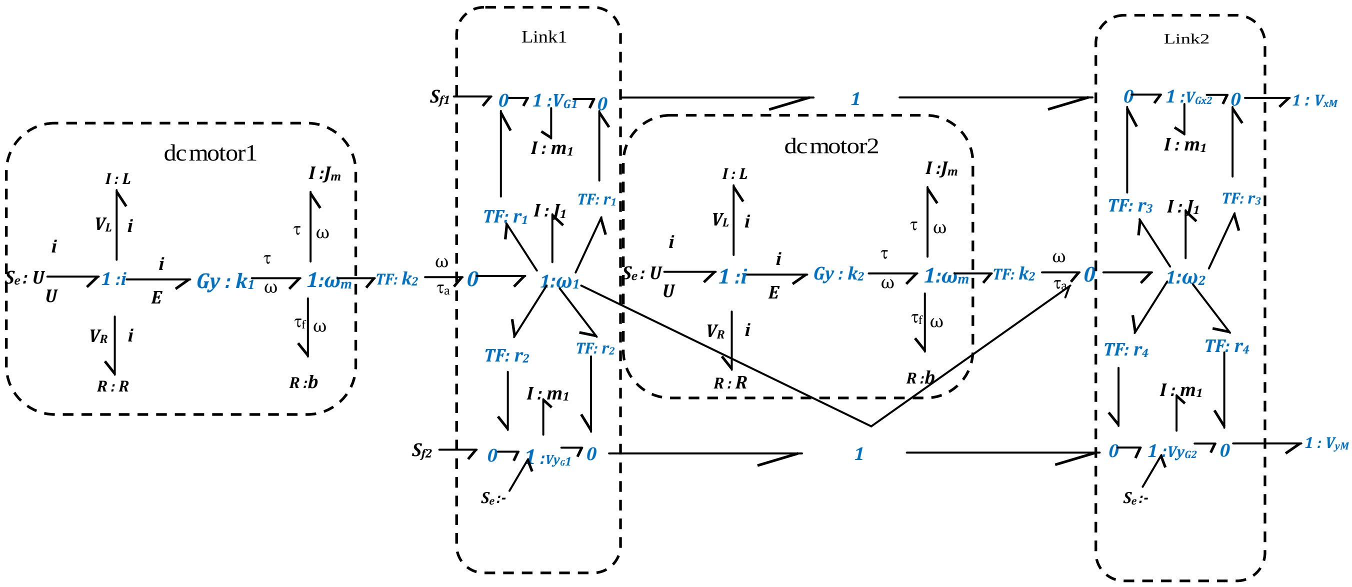


Figure 5: Bond graph of the two arm manipulator

The junction equations and elements are illustrated in Tables I and II.

Table. I. The junction's characteristic

Jonctions « 1 »		
$1:\begin{cases} e_1 - e_3 - e_4 - e_8 - e_{10} - e_{14} - e_{26} = 0 \\ f_1 = f_3 = f_4 = f_8 = f_{10} = f_{14} = f_{26} \end{cases}$	$1:\begin{cases} f_5 = f_6 = f_7 \\ e_6 + e_7 - e_5 = 0 \end{cases}$	$1:\begin{cases} f_9 = f_{18} \\ e_{18} - e_9 = 0 \end{cases}$
$1:\begin{cases} e_2 - e_{16} - e_{17} - e_{19} - e_{25} = 0 \\ f_{25} = f_{16} = f_{17} = f_2 = f_{19} \end{cases}$	$1:\begin{cases} f_{12} = f_{11} \\ e_{12} - e_{11} = 0 \end{cases}$	$1:\begin{cases} e_{21} - e_{23} - e_{22} = 0 \\ f_{21} = f_{22} = f_{23} \end{cases}$

Jonction « 0 »		
$0:\begin{cases} e_{25} = e_{26} = e_{27} \\ f_{26} - f_{27} + f_{25} = 0 \end{cases}$	$0:\begin{cases} e_{13} = e_{12} = e_{15} \\ f_{15} + f_{13} - f_{12} = 0 \end{cases}$	$0:\begin{cases} e_{20} = e_{21} = e_{24} \\ f_{20} + f_{24} - f_{21} = 0 \end{cases}$

Jonctions « TF»		
$TF:k_1\begin{cases} e_3 = k_1 * e_{18} \\ f_{18} = k_1 * f_3 \end{cases}$	$TF:k_2\begin{cases} e_8 = k_2 * e_7 \\ f_{18} = k_1 * f_3 \end{cases}$	$TF:k_3\begin{cases} e_{14} = k_3 * e_{13} \\ f_{13} = k_3 * f_{14} \end{cases}$
$TF:k_4\begin{cases} e_{16} = k_4 * e_{15} \\ f_{15} = k_4 * f_{15} \end{cases}$	$TF:k_5\begin{cases} e_{19} = k_5 * e_{20} \\ f_{20} = k_5 * f_{19} \end{cases}$	$TF:k_6\begin{cases} e_{10} = k_6 * e_{24} \\ f_{24} = k_6 * f_{10} \end{cases}$

Table.II. The equations of elements

Element				
$I_1 : e_4 = I_1 \dfrac{df_4}{dt}$	$m_2 : e_{11} = m_2 \dfrac{df_{11}}{dt}$	$m_1 : e_5 = m_1 \dfrac{df_5}{dt}$	$-P_1 : e_6 = -m_1 g$	$S_{e1} : e_1 = \tau_1$ $S_{e2} : e_2 = \tau_2$
$m_1 : e_1 = m_1 \dfrac{df_1}{dt}$	$m_2 : e_{22} = m_2 \dfrac{df_{22}}{dt}$	$-P_2 : e_{23} = -m_2 g$	$I_2 : e_{17} = I_2 \dfrac{df_{17}}{dt}$	$I_2 : e_{27} = I_{27} \dfrac{df_{27}}{dt}$

The torque applied to move link 1 can be obtained from the bond graph by the Eq. (1) and the external torque applied to move the second link by the Eq. (2).

$$\tau_1 = e_1 = e_3 + e_4 + e_8 + e_{10} + e_{14} + e_{26} \quad (13)$$
$$\tau_2 = e_2 = e_{16} + e_{17} + e_{19} + e_{25} \quad (14)$$

From the bond graph model and the precedent junction equations and elements we can formulate a set of manipulator robot differential equations in the following matrix form:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}M_{11}(q) & M_{12}(q)\\ M_{21}(q) & M_{22}(q)\end{bmatrix}\begin{bmatrix}\ddot{q}_1\\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix}C_{11}(q,\dot{q}) & C_{12}(q,\dot{q})\\ C_{21}(q,\dot{q}) & C_{22}(q,\dot{q})\end{bmatrix}\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix} + \begin{bmatrix}G_1(q)\\ G_2(q)\end{bmatrix} \quad (15)$$

Where:
The elements of the inertia matrix M (q) in the terms of the parameters of the robot manipulator are given by:

$M_{11}(q) = I_1 + I_2 + m_1 l_{c1}^2 + m_2 l_{c2}^2 + m_2 l_1^2 + 2m_2 l_1 l_{c2} c_2$ $\qquad M_{12}(q) = M_{21}(q) = I_2 + m_2 l_{c2}^2 + 2m_2 l_1 l_{c2} c_2$

$M_{22}(q) = 2I_2 + m_2 l_{c2}^2$

The matrix elements $C_{ij}(q,\dot{q})(i, j = 1,2)$ centrifugal and Coriolis force are:

$C_{11}(q,\dot{q}) = -m_2 l_1 l_{c2} \dot{q}_2 s_2$

$C_{12}(q,\dot{q}) = -m_2 l_1 l_{c2} s_2 (\dot{q}_1 + \dot{q}_2)$

$C_{21}(q,\dot{q}) = m_2 l_1 l_{c2} \dot{q}_1 s_2$

$C_{22}(q,\dot{q}) = 0$

Finally the elements of the vector of gravitational torques G (q) are given by:

$G_1(q) = (m_1 + m_2) g l_{c1} c_1 + m_2 g l_{c2} c_{12}$

$G_2(q) = m_2 g l_{c2} c_{12}$

The equations of external torque given by bond graph approach correspond to those obtained using Lagrange methods, as illustrated in Eq. (8).
This indicates that, the model developed capture the essential aspects of rigid body dynamics of the robot manipulator.

5. Conclusion

A new approach is used in this paper for modelling a robot arm. From the Bond graph model we can formulate the differential equations, this last one describe all behaviours of the system.

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